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WIND-TUNNEL INVESTIGATION
OF SONIC-BOOM CHARACTERISTICS
OF TWO SIMPLE WING MODELS AT
MACH NUMBERS FROM 2.3 TO 4.63

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16. Abstract

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SUMMARY

A wind-tunnel investigation was undertaken to provide experimental data which will be useful in studying lift-induced sonic-boom characteristics at high supersonic Mach numbers. Pressure signatures below two simple wing models were measured at two separation distances for a range of lift coefficients from 0 to about 0.1 at Mach numbers of 2.3, 2.96, 3.83, and 4.63. Comparisons of theoretical and experimental pressure signatures showed that the good agreement obtained for the lowest Mach number of this investigation, and in previously reported test programs for moderate supersonic speeds, does not persist into the higher Mach number range, particularly for high lift coefficients. In all instances, the overall signature correlation became worse with increasing Mach number and with increasing lift coefficient. Although the generally observed tendency toward increasing applicability of the theory at large distances appeared to be supported by the results of this investigation, good correlation even for very large distances at the highest Mach number seemed to be precluded by substantial differences between theoretical impulse and experimental impulse. Impulse comparisons indicated that even at extremely large distances, experimental and theoretical overpressures could differ by as much as 20 percent.

INTRODUCTION

In recent years, a substantial effort has been made to provide the necessary experimental data required to verify and refine current sonic-boom estimation techniques. (See, for example, ref. 1.) The results of wind-tunnel investigations (refs. 2 to 5) and flight test programs (refs. 2 and 6) show that existing methods are effective in providing reasonably accurate predictions of sonic-boom characteristics for Mach numbers as high as 2.5 to 3.0.

Several investigations (refs. 7 and 8) have explored the sonic-boom phenomena at higher Mach numbers where the small-disturbance assumptions of linearized theory may not apply and, consequently, present sonic-boom estimation techniques would not be applicable. The results seem to indicate that the good correlation between experiment and theory at moderate Mach numbers may not persist at higher ones, particularly in the near field. In reference 9, sonic-boom tests of simple bodies of revolution were made at Mach numbers from 2.96 to 4.63. The results showed existing theories to be inadequate in predicting volume effects at high Mach numbers, especially for blunt-nose or small-fineness-ratio bodies. There is also some evidence (ref. 8) that the discrepancies between experiment and theory at high Mach numbers will be more pronounced for lifting than nonlifting conditions; however, definite conclusions cannot be drawn from the limited amount of available experimental data.

The present investigation was undertaken to provide experimental data which will be useful in studying lift-induced sonic-boom characteristics at high supersonic Mach numbers. The data presented herein extend the results of reference 9 which pertain to sonic-boom characteristics of nonlifting bodies of revolution. Pressure signatures below two simple wing models were measured at two separation distances for a range of lift coefficients at Mach numbers of 2.3, 2.96, 3.83, and 4.63.

<center>SYMBOLS</center>

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

A	cross-sectional area of model determined by supersonic-area-rule cutting planes having an angle μ with respect to the streamwise axis
B	equivalent cross-sectional area due to lift, $\dfrac{\beta}{2q} \displaystyle\int_0^x F_L\, dx$
C_L	lift coefficient, Lift/qS
$C_{L\alpha}$	lift-curve slope, $\partial C_L/\partial\alpha$ at $\alpha = 0^\circ$
F_L	lifting force per unit length along longitudinal axis of model
h	perpendicular distance from model to measuring probe

2

l model reference length

M Mach number

p reference pressure (free-stream static)

Δp incremental pressure due to flow field of model

Δp_{max} maximum value of Δp at bow shock

q free-stream dynamic pressure

S model planform area

x distance measured along longitudinal axis from model nose

Δx distance from point on pressure signature to point where pressure-signature curve crosses zero-pressure reference axis

α angle of attack

$\beta = \sqrt{M^2 - 1}$

μ Mach angle, $\sin^{-1} \dfrac{1}{M}$

MODELS AND TESTS

Drawings of the test models are shown in figure 1. Model A was designed to employ component arrangements typical of a lifting reentry-type configuration, whereas the design of model B more nearly typifies present-day hypersonic-transport concepts. The overall designs were kept simple to facilitate analysis. Both models were 7.62 cm (3 in.) long, constructed of stainless steel, and built to accommodate a miniature internal strain-gage balance. The strain-gage balance provided a direct measurement of the model's normal force which was an improvement over the method employed in previous tests which required the calculation of normal force based on measured values of angle of attack. Provisions were made for mounting a prism flush with the model surface for optically sensing angle of attack.

The tests were conducted in the high Mach number test section of the Langley Unitary Plan wind tunnel at Mach numbers of 2.3, 2.96, 3.83, and 4.63 with corresponding stagnation pressures of 41 kN/m^2 (6.0 psi), 69 kN/m^2 (10.0 psi), 193 kN/m^2 (28.0 psi), and 414 kN/m^2 (60.0 psi), respectively. The large variation in stagnation pressure with Mach number was necessary to maintain reasonable levels of static pressure so that the same pressure measuring equipment could be used for all test Mach numbers. The stagnation temperature for all Mach numbers was 338.7^o K (150° F), and the Reynolds number based on model length of 7.62 cm (3 in.) varied from 0.275 × 10^6 at M = 2.3 to 0.8 × 10^6 at M = 4.63. Both model and measuring probe were mounted on support systems which provided for remotely controlled adjustments of model and probe positions. The model angle of attack was set remotely by a miniature angle-of-attack mechanism and was measured by using a small prism recessed in the model. The normal force was measured by a miniature one-component internal strain-gage balance with a design load of 2.7 N (0.6 lb). A sketch of the test apparatus is shown in figure 2.

The measuring probe was a slender cone (2° half-angle cone) with four 0.0889-cm-diameter (0.035 in.) static-pressure orifices leading to a common chamber. Orifices were circumferentially spaced 90° apart around the probe and were arranged to lie in a Mach 2.92 cone originating at the model. For the Mach number range of the tests, changes in the Mach angle with respect to the orifice locations will have no significant effect on the measured pressures. The pressures were measured by using a differential pressure gage with a 1.034-kN/m^2 (0.15 psi) design load. Further details on wind-tunnel sonic-boom testing techniques are given in reference 2.

THEORETICAL CONSIDERATIONS

The method for determining the pressure signatures in the flow field of the test models is based on the theoretical work of reference 10 and has been implemented by a machine program described in reference 11. The two simple wing models considered in this investigation are completely described to the program by an effective area distribution A due to volume and by an effective area distribution B due to flat-plate lift. Figure 3 shows the effective area distributions used in obtaining the theoretical pressure signature below model A at a Mach number of 2.96 and a lift coefficient of 0.1. The effective area distribution A due to volume is evaluated through employment of supersonic-area-rule concepts (the cross-sectional area at any longitudinal station being determined by the frontal projection of the model area intercepted by a plane passing through the given longitudinal station and inclined at the Mach angle). Note that the areas as used herein take into account the model angle of attack; that is, the Mach angle is measured with respect to the free-stream direction and not with respect to the

model axis. The model angle of attack used in making the theoretical estimations is obtained from measured lift-curve slopes given in the following table:

M	c_{L_α}	
	Model A	Model B
2.3	0.0158	0.028
2.96	.0150	.022
3.83	.0138	.018
4.63	.0129	.015

The supersonic-zero-lift-wave-drag computer program described in reference 12 has been used in the determination of the areas for the models of these tests. The area distributions include contributions from the miniature sting upon which the models were mounted.

The area due to the distribution of flat-plate lift is evaluated by use of the following relationship:

$$B = \frac{\beta}{2q} \int_0^x F_L \, dx$$

where the integration is performed along the model axis. The lifting force per unit length F_L along the model axis is obtained by use of the computer program described in reference 13. The lift contribution to the effective area is obtained by transferring the values of B from the model axis to the streamwise axis along a Mach plane in a manner similar to that used in evaluating the volume effects.

Following the reasoning of reference 14, the combined effective areas due to volume and lift describe a body of revolution which has the same flow-field characteristics as the model which it replaces. This method of analysis which employs supersonic-area-rule considerations is described in more detail in reference 15 and has been particularly suitable at moderate supersonic Mach numbers for evaluating the sonic-boom characteristics of models at lifting conditions since it provides a good approximation to the proper superposition of disturbances.

EXPERIMENTAL RESULTS

Experimental pressure signatures for the test models A and B are shown in figures 4 and 5, respectively. Each of these figures is divided into six parts (a to f) which

present data for Mach number M and nondimensional model-probe separation distance h/l as noted in the following table:

Figure part Test condition	a	b	c	d	e	f
M	2.3	2.96	2.96	3.83	4.63	4.63
h/l	4	4	2	4	4	2

Each figure part contains four pressure signatures corresponding to the four lifting conditions at a particular value of M and h/l. Signature pressures and distances are presented in the parametric form of $\dfrac{\Delta p}{p}\left(\dfrac{h}{l}\right)^{3/4}$ and $\dfrac{\Delta x}{l}\left(\dfrac{h}{l}\right)^{-1/4}$, respectively.

The data of figures 4 and 5 show the influence of lift on pressure signature characteristics for a lift-coefficient range from 0 to about 0.1. The most obvious effect is the large increase in maximum overpressure parameter produced by increased lift. This effect is most pronounced for model A at the lower Mach numbers where the increased lift causes a transition in signature characteristics from near-field to far-field shapes.

COMPARISON OF EXPERIMENT AND THEORY

Figures 6 and 7 show the experimental and theoretical pressure signatures for models A and B, respectively. For each model the smallest and largest lift coefficients of the tests at Mach numbers of 2.3, 2.96, and 4.63 are presented for a separation distance corresponding to $h/l = 4$. Above each signature is a sketch of the model indicating the model orientation relative to the Mach lines which are shown dashed. For general signature characteristics which include signature shape as well as location and strength of shocks, relatively good agreement between experiment and theory is seen in figure 6 at all three Mach numbers for the more slender model A at zero-lift conditions. For the same model at $C_L = 0.1$, the theoretically predicted maximum overpressures agree well with experimental values; however, sizable discrepancies in signature shape are encountered, especially in the expansion region where the slope of the theoretical signature is always equal to or less than that measured. In figure 7, similar discrepancies of a larger magnitude are shown for model B at nonlifting as well as lifting conditions. Except for model A at zero lift, the correlation between experiment and theory is poor and becomes worse with an increase in Mach number.

It should be pointed out that the measurements were made relatively close to the model where difficulty might be expected in the prediction of signature characteristics using a theory based on far-field assumptions. Although it can be shown that signature shape correlation improves with an increase in distance for the results of these tests, the possibility of obtaining good correlation at large distances seems to be precluded by sizable differences in measured and calculated values of signature impulse which is discussed subsequently.

Figure 8 shows the variation in maximum overpressure parameter with Mach number for $C_L = 0$ and 0.1. For the two largest Mach numbers (M = 3.83 and 4.63), the experimental values of maximum overpressure (ticked symbols) were extrapolated from $C_L = 0.09$ to $C_L = 0.1$. The data in figure 8 show that increasing the Mach number results in moderate increases in overpressure. It can be seen that reasonable agreement was obtained between the theoretical and experimental overpressure values, and the agreement was unexpectedly better for the lifting conditions at which the largest discrepancies occur in signature shape.

The impulse parameter provides a measure of the relative bow shock overpressures that would be realized at large distances where an N-wave signature is approached; consequently, a comparison of the calculated and measured impulse parameters serves as an assessment of the correlation expected to be found at large distances. Variations of signature impulse parameter with Mach number are shown in figure 9 for $C_L = 0$ and 0.1. The ticked symbols again denote an extrapolation from $C_L = 0.09$ to $C_L = 0.1$. The impulse parameter was nondimensionalized by including the distance ratio h/l; the impulse parameter in this form is invariant with distance. The integration for the impulse area was carried out from the bow shock to that point on the signature which gives the largest value for the integral. (For the typical N-wave signature, this would include the area under the forward portion of the signature as shown in the inset sketch of fig. 9.) The data in figure 9 show that increasing the Mach number results in moderate increases in impulse parameter for $C_L = 0$ and substantially larger increases for $C_L = 0.1$. At $C_L = 0$ the agreement between experimental impulse and theoretical impulse is reasonably good over the complete Mach number range; however, at $C_L = 0.1$ discrepancies appear and tend to become more pronounced with increasing Mach number. At large distances the overpressure is proportional to the square root of the impulse; thus, even at large distances the experimental and theoretical overpressures would be expected to differ by as much as 20 percent for the largest values of C_L and M.

Summary plots of impulse parameter as a function of lift parameter for all pressure signatures measured are presented in figure 10. In this figure, the parametric form of the impulse includes not only the distance ratio h/l but also Mach number effects. The theoretical impulse parameter is shown as a shaded band in order to

account for the variations of effective area distribution with Mach number and angle of attack. In general, the agreement between experiment and theory is not as good for the larger values of lift parameters as it is for the smaller ones. Overall the agreement appears to be better for the more slender model A and for the smaller Mach numbers.

CONCLUDING REMARKS

A wind-tunnel investigation to determine high Mach number lift-induced sonic-boom characteristics of two simple wing models was conducted at Mach numbers of 2.3, 2.96, 3.83, and 4.63 over a lift-coefficient range from 0 to about 0.1. Comparisons of theoretical and experimental pressure signatures showed that the detailed signature shape was predicted to a greater degree of accuracy at the lower Mach numbers and at the lower lift coefficients. In all instances the overall signature correlation became worse as the Mach number and the lift coefficient increased. It was noted, however, that at the higher lift coefficients where the experimental and theoretical signature-shape differences were more pronounced, there was an unexpected improvement in maximum overpressure correlation. Although the generally observed tendency toward improved signature correlation with an increase in distance appears to be supported by the results of this investigation, the good correlation usually expected at large distances seems to be precluded by substantial differences between the experimental impulse and theoretical impulse. Impulse comparisons indicate that even at extremely large distances, experimental and theoretical overpressures would be expected to differ by as much as 20 percent.

Langley Research Center,
    National Aeronautics and Space Administration,
        Hampton, Va., March 23, 1971.

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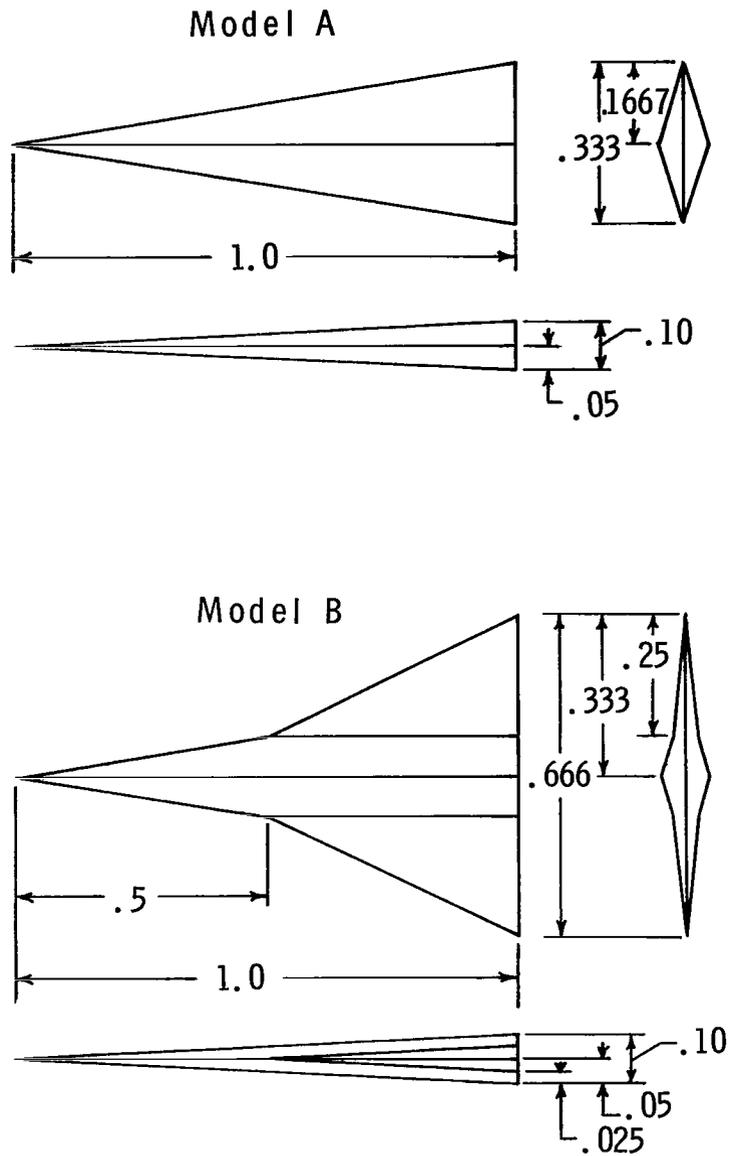
Model A

Model B

Figure 1.- Sonic-boom test models. All dimensions are nondimensionalized with
respect to model length l of 7.62 cm (3 in.).
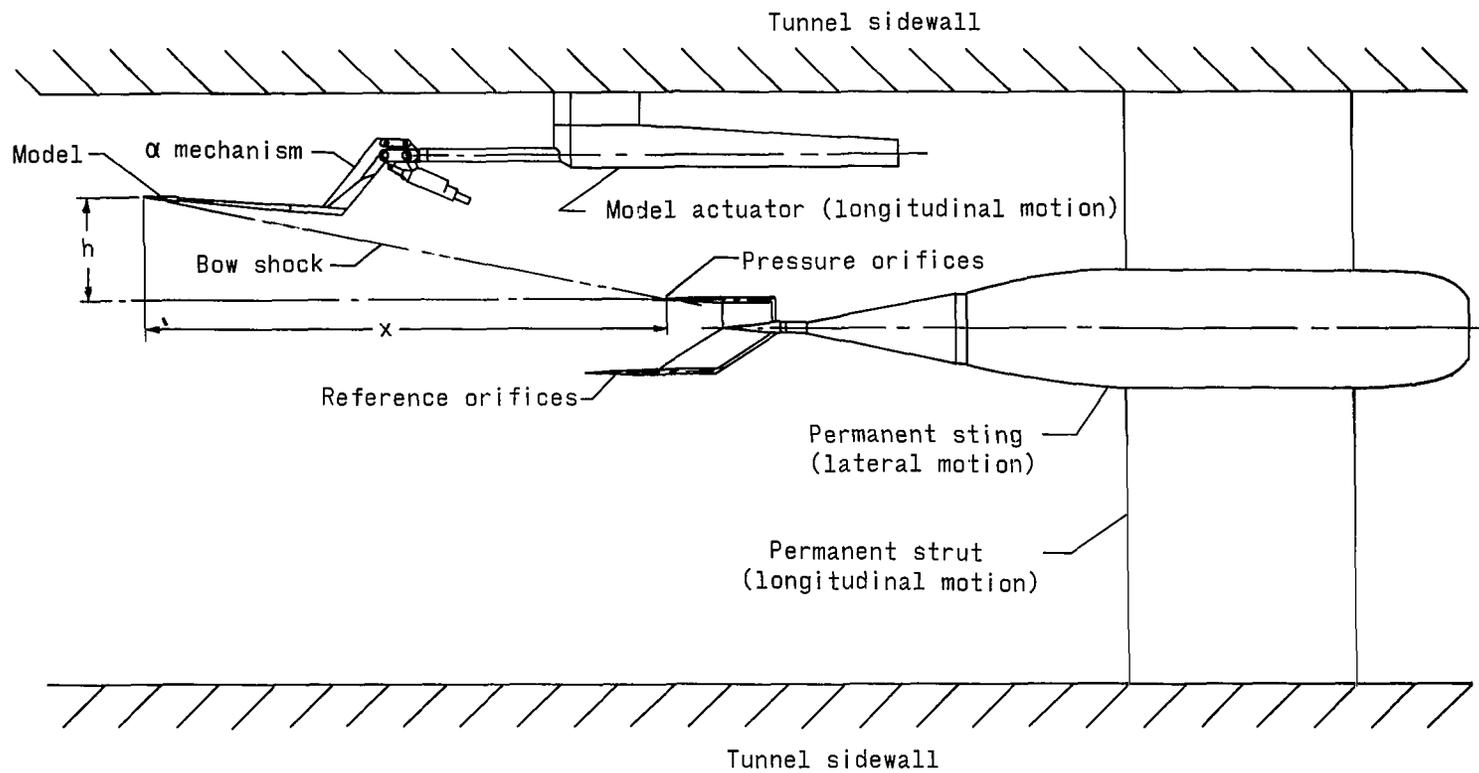
Figure 2.- Wind-tunnel apparatus.
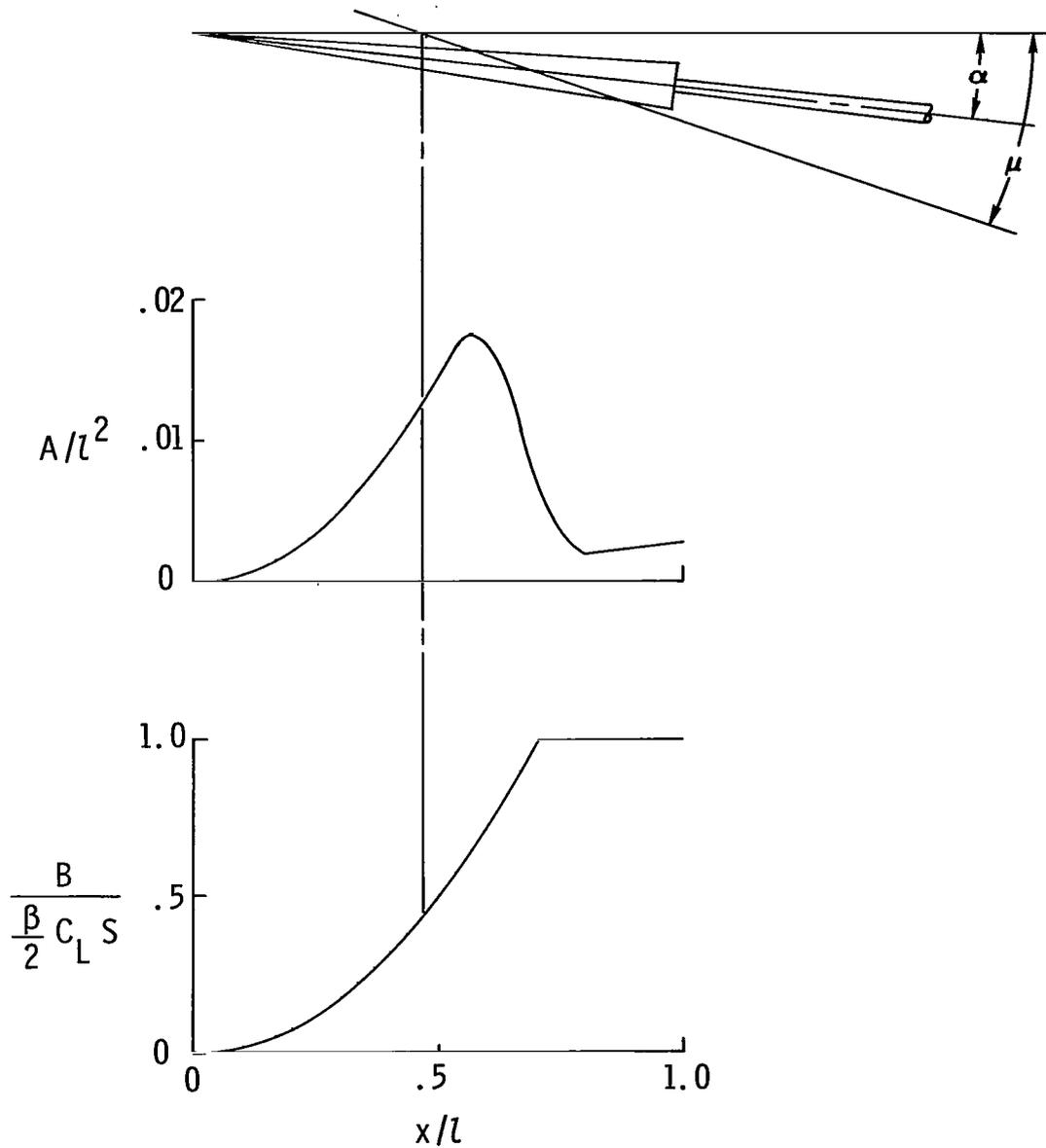
Figure 3.- Illustrative effective area distributions.   Model A;   M = 2.96; C_L = 0.1.
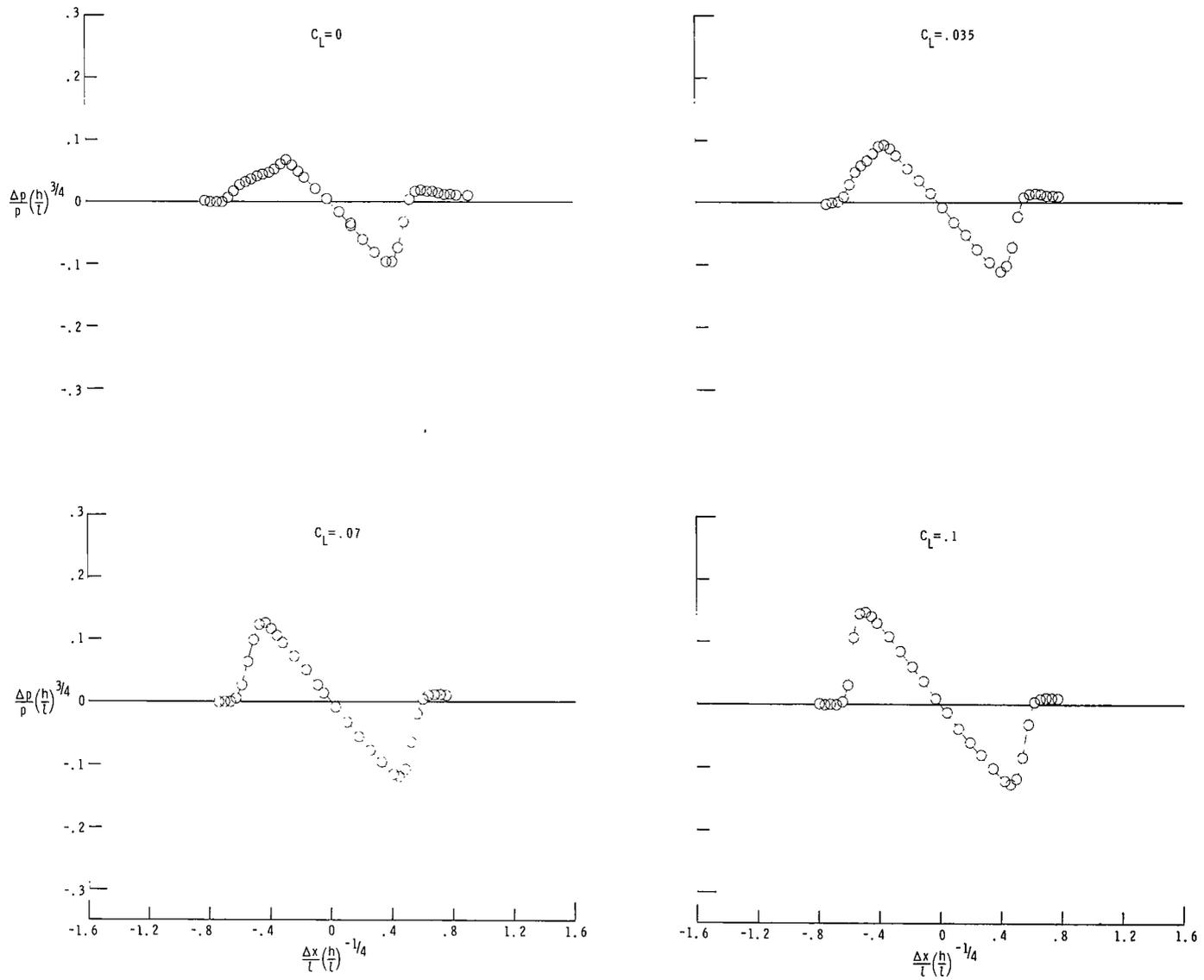
(a)   M = 2.3;   h/l = 4.

Figure 4.- Pressure distributions in the flow field of model A.
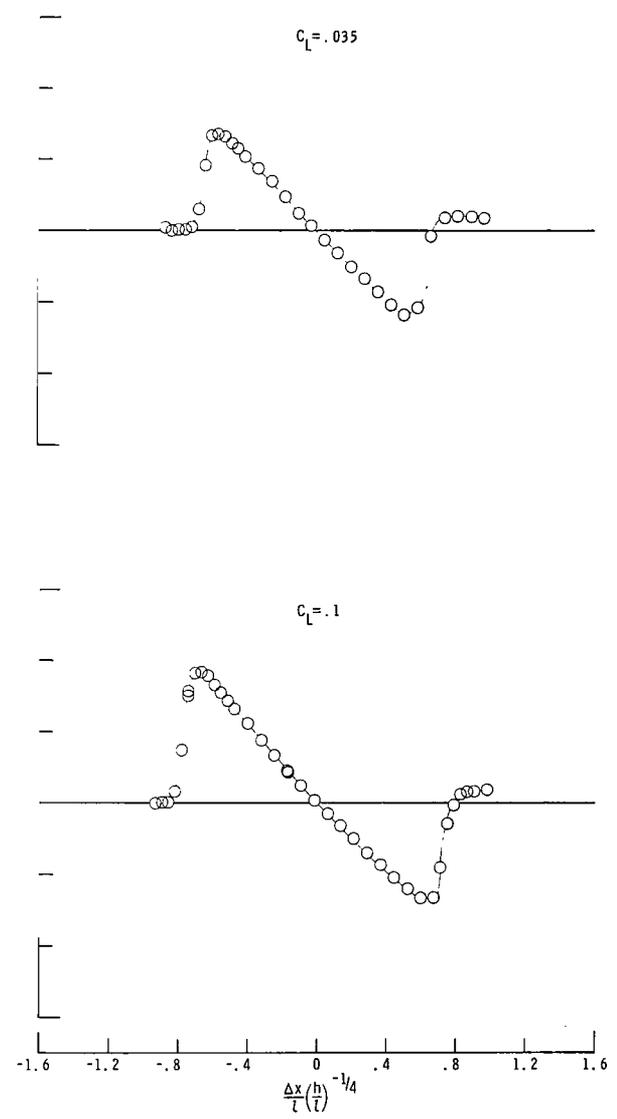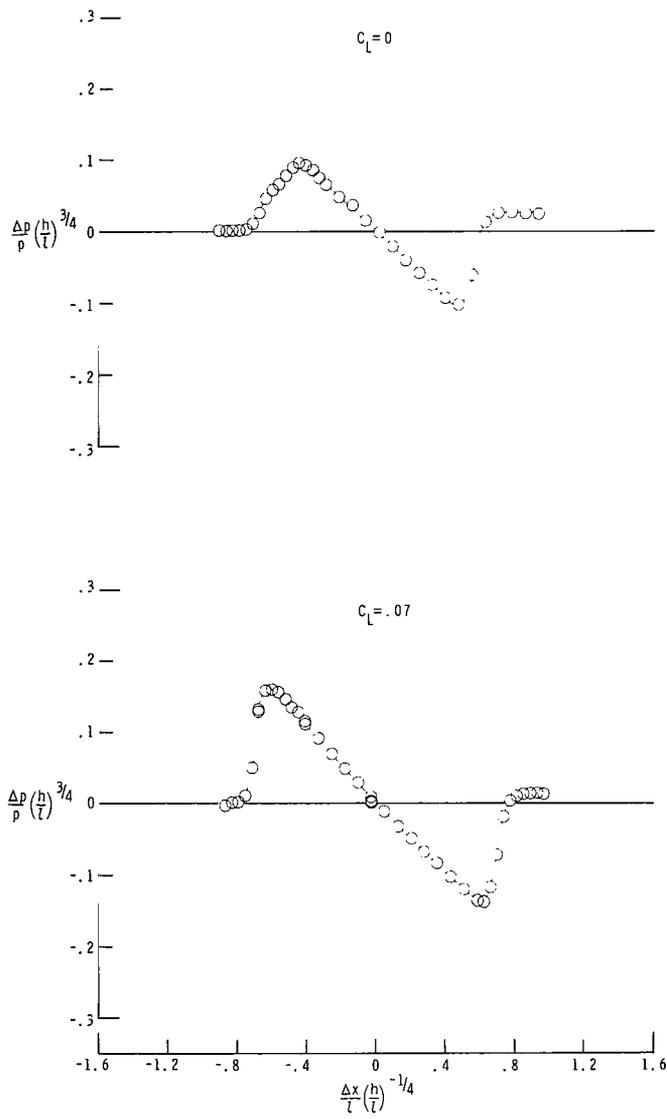
(b)   M = 2.96;   h/l = 4.

Figure 4.- Continued.
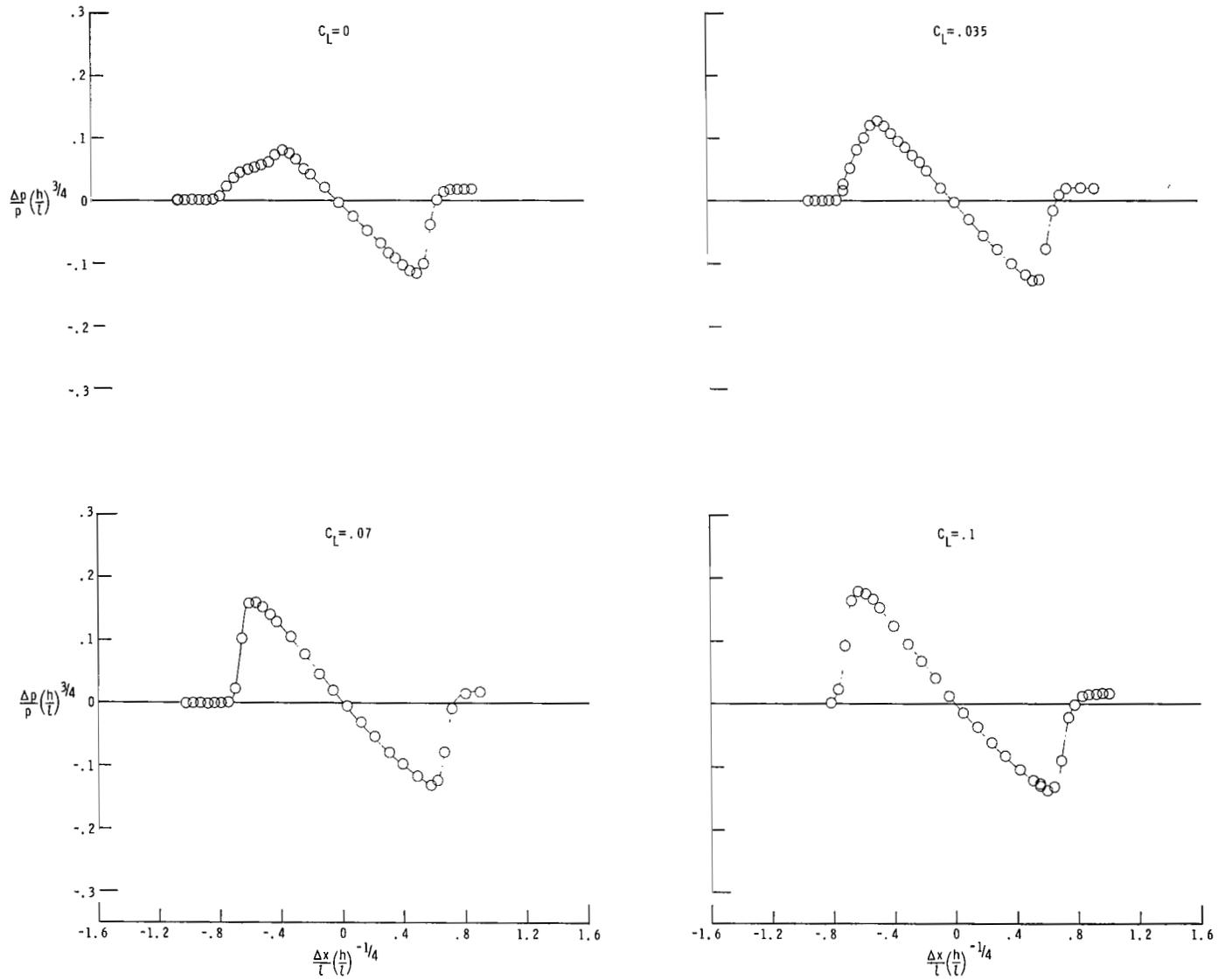
(c) M = 2.96; h/l = 2.

Figure 4.- Continued.
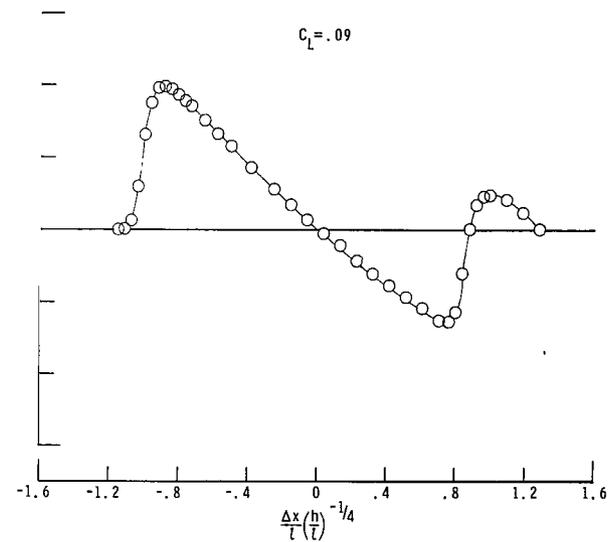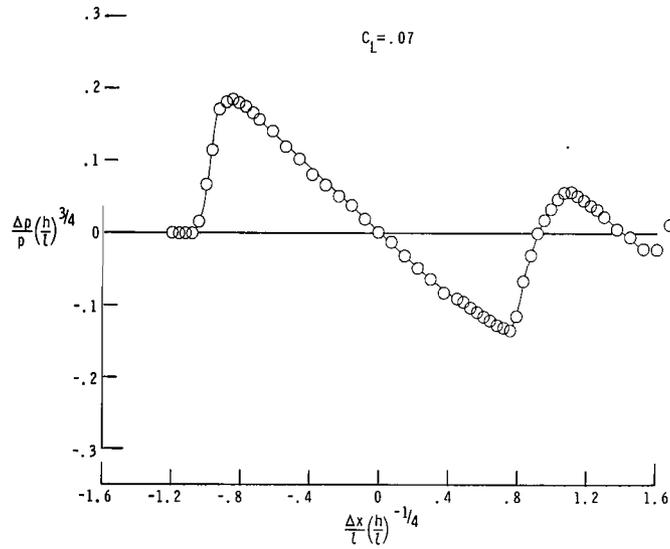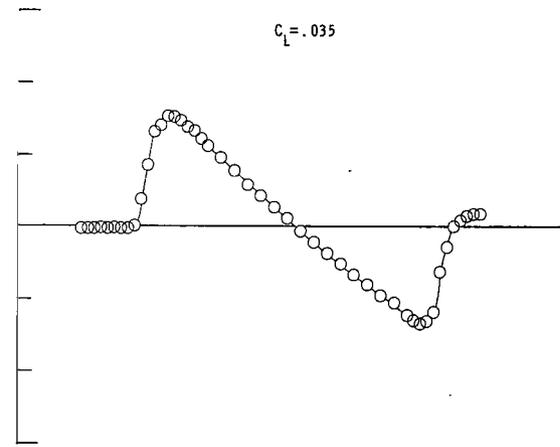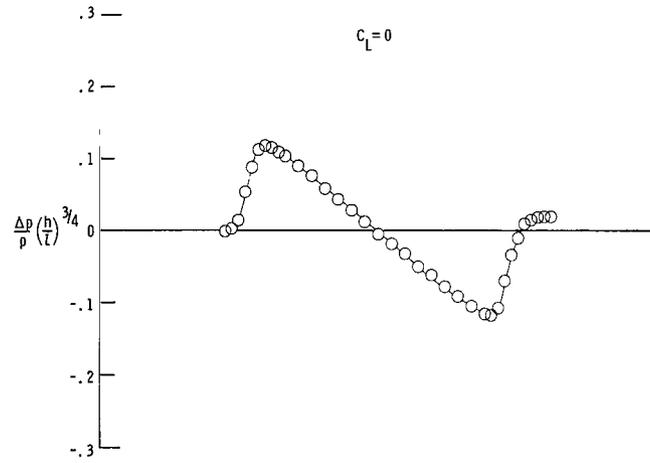
(d) M = 3.83; h/l = 4.

Figure 4.- Continued.
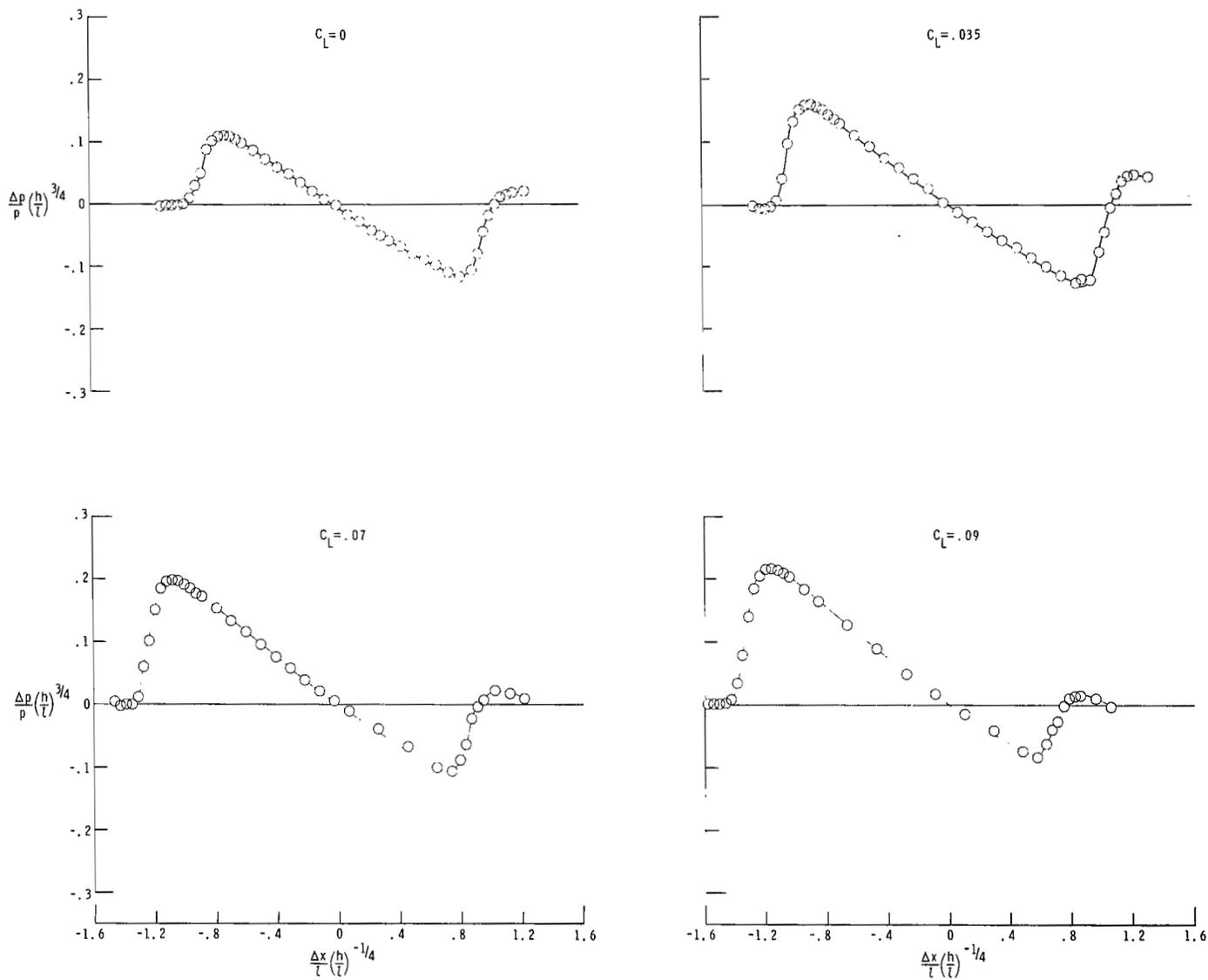
(e)   M = 4.63;   h/l = 4.

Figure 4.- Continued.
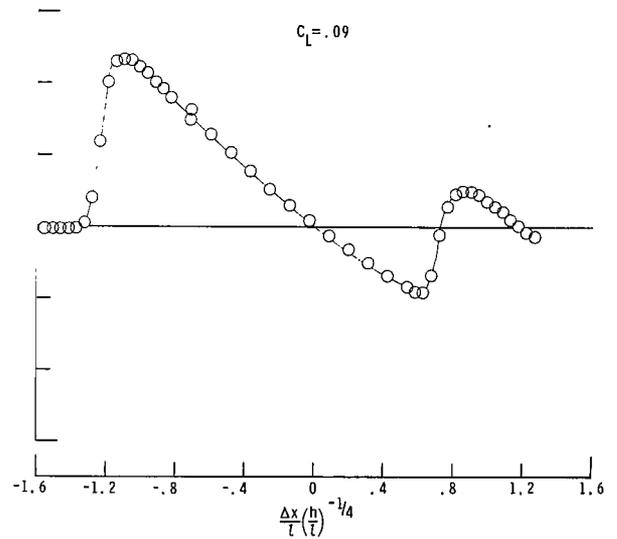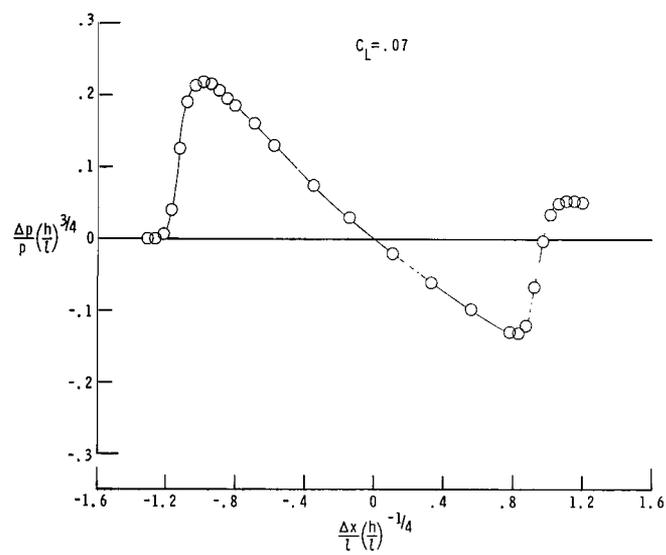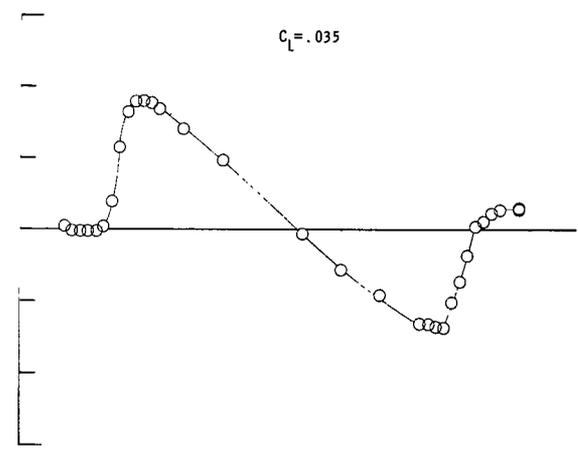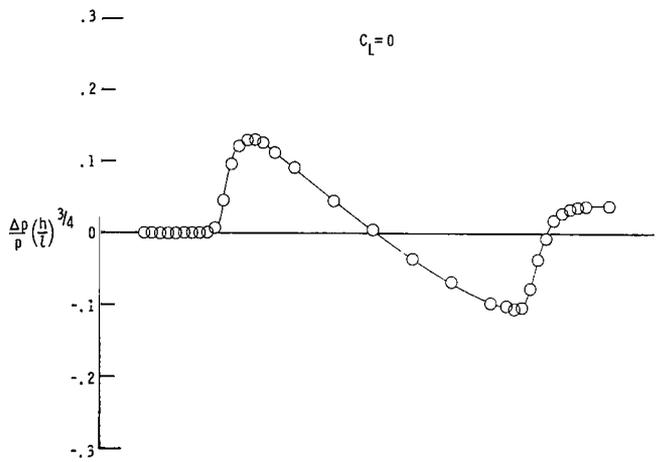
(f)   M = 4.63;   h/l = 2.

Figure 4.- Concluded.
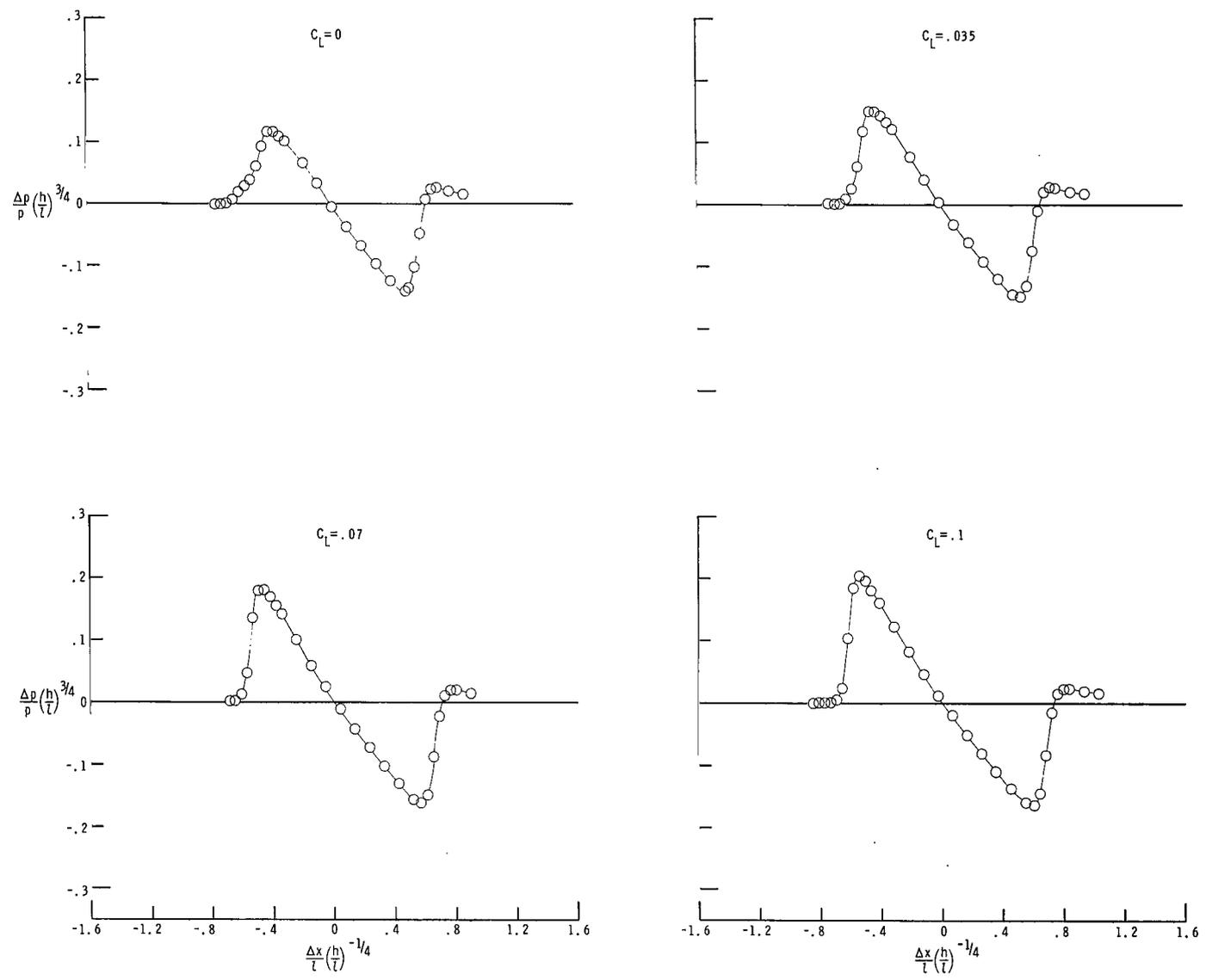
(a) M = 2.3; h/l = 4.

Figure 5.- Pressure distributions in the flow field of model B.

$$\frac{\Delta p}{p}\left(\frac{h}{l}\right)^{3/4}$$

$C_L = 0$

$C_L = .035$

$C_L = .07$

$C_L = .1$

$$\frac{\Delta x}{l}\left(\frac{h}{l}\right)^{-1/4}$$
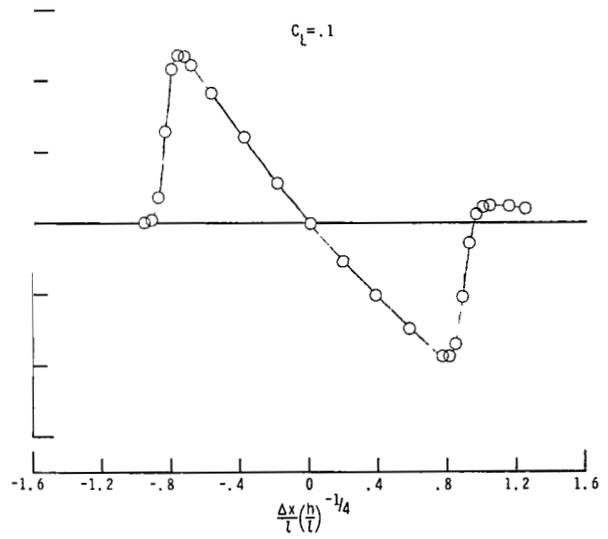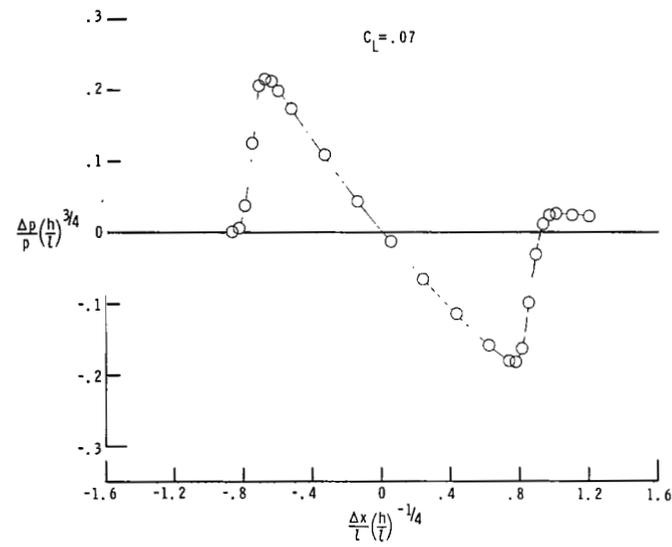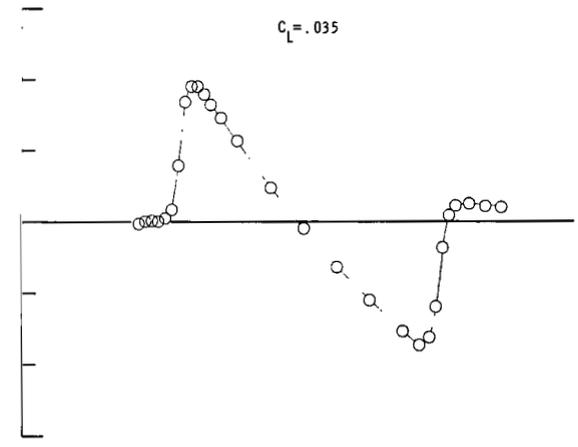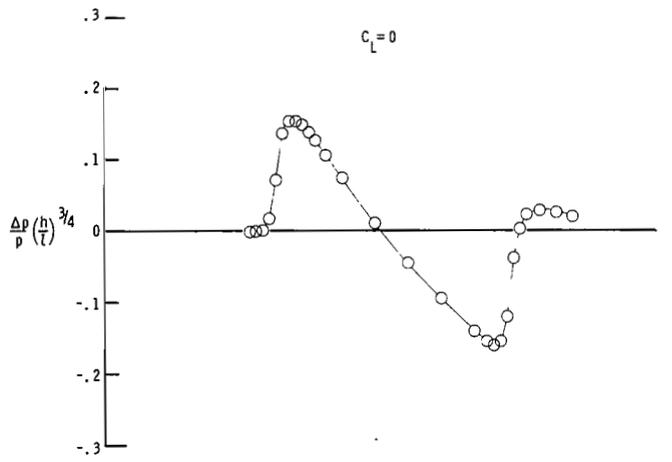
(b)   M = 2.96;   h/l = 4.
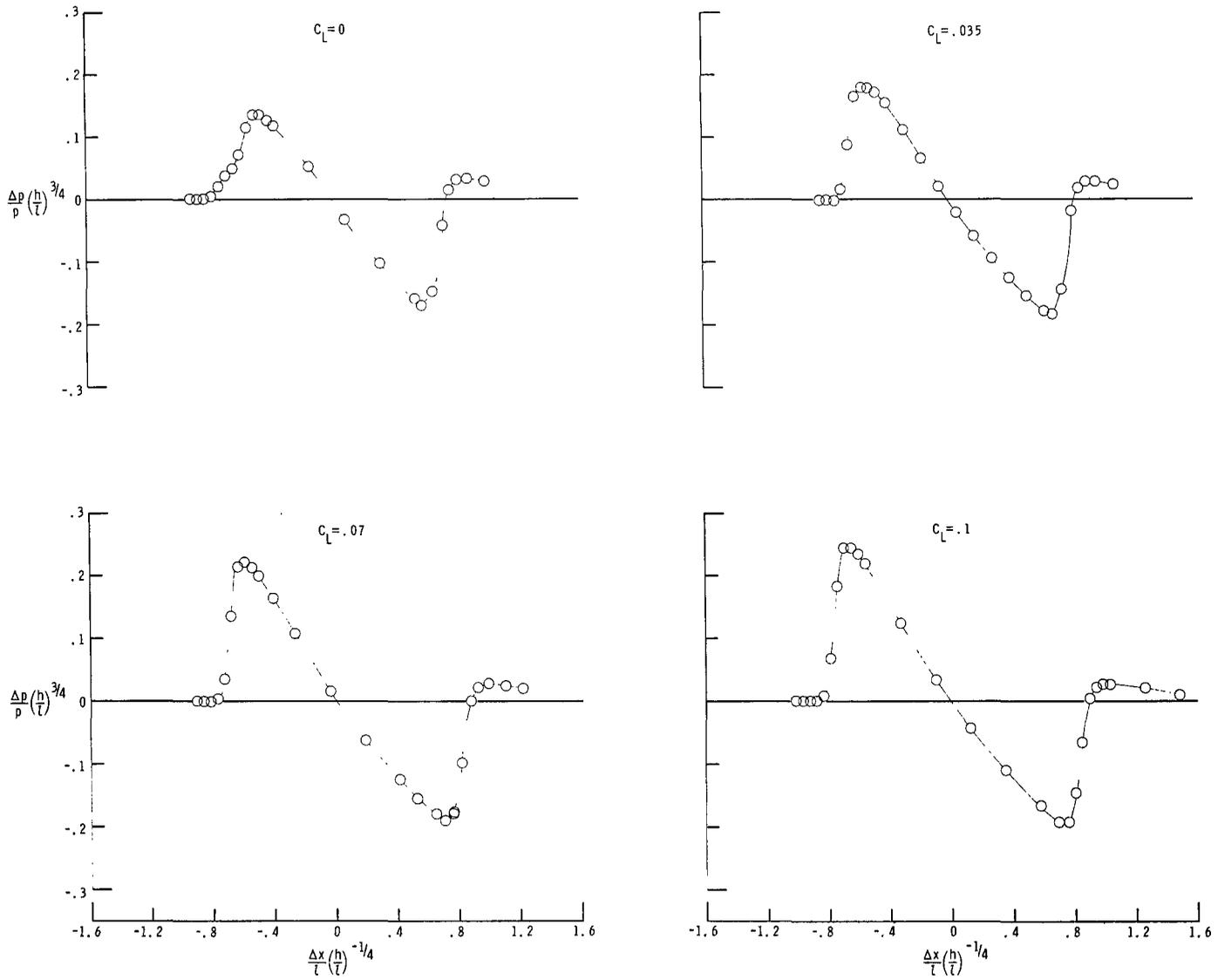
Figure 5.- Continued.

(c)   M = 2.96;   h/l = 2.

Figure 5.- Continued.
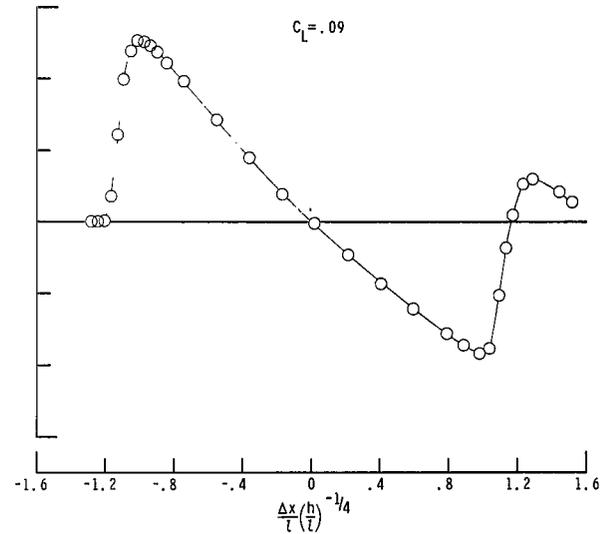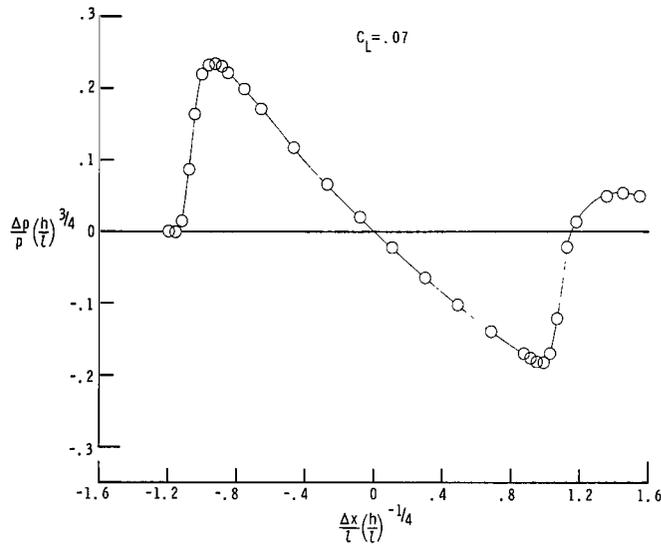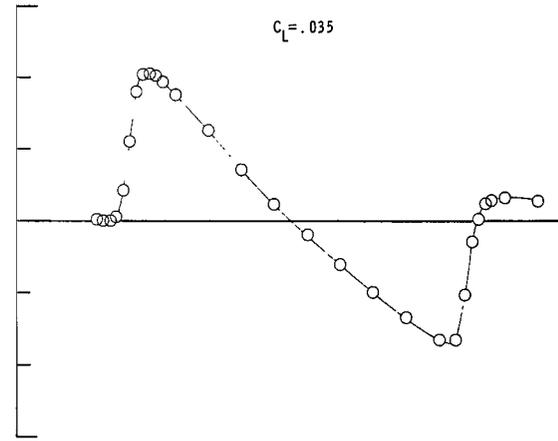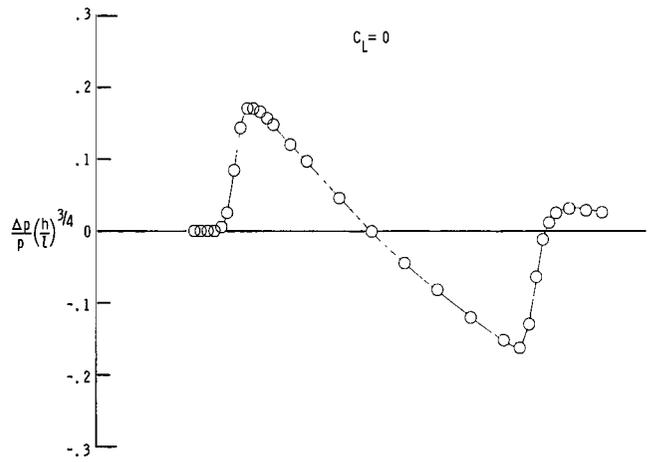
(d) M = 3.83; h/l = 4.

Figure 5.- Continued.
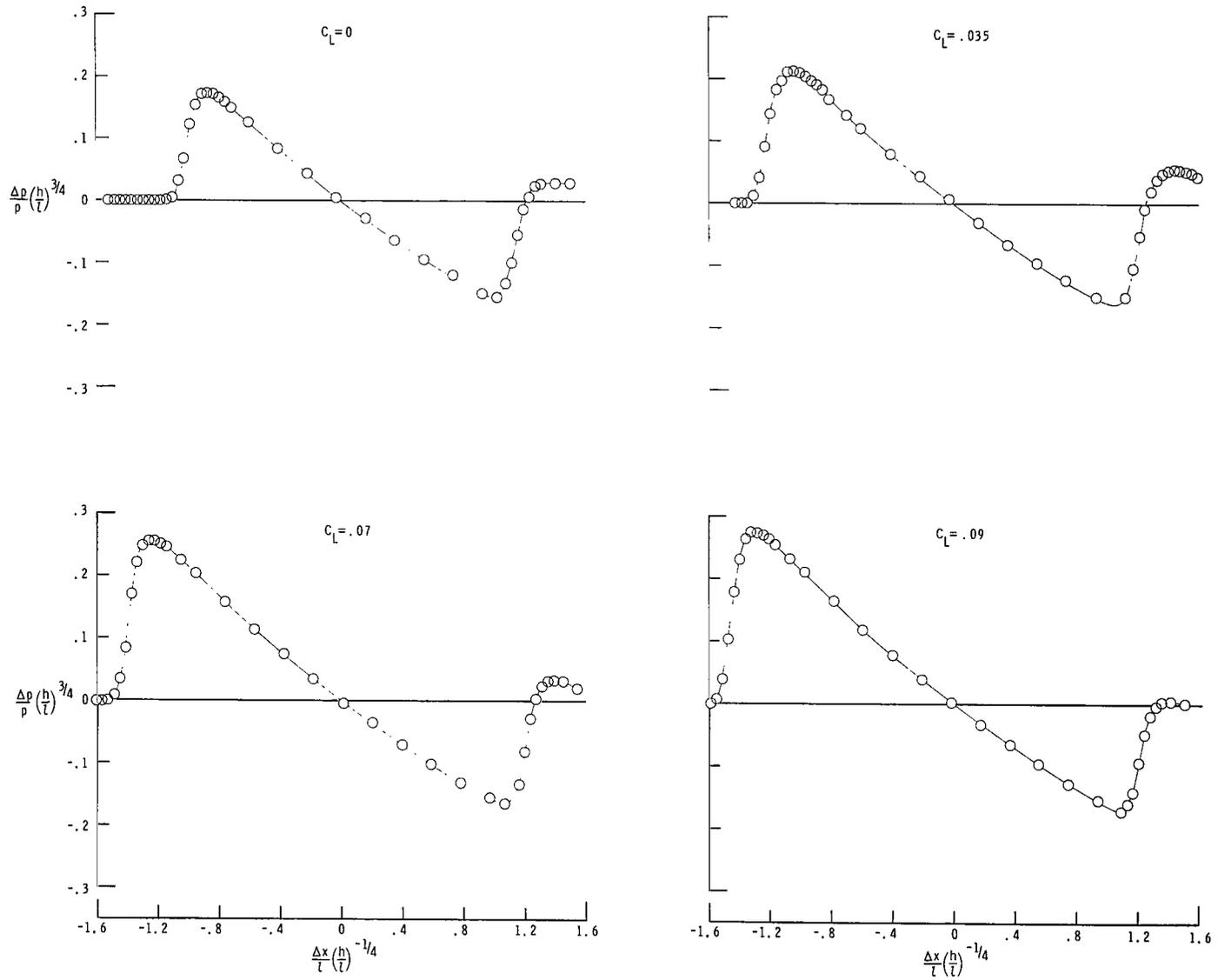
(e)   M = 4.63;   h/l = 4.

Figure 5.- Continued.
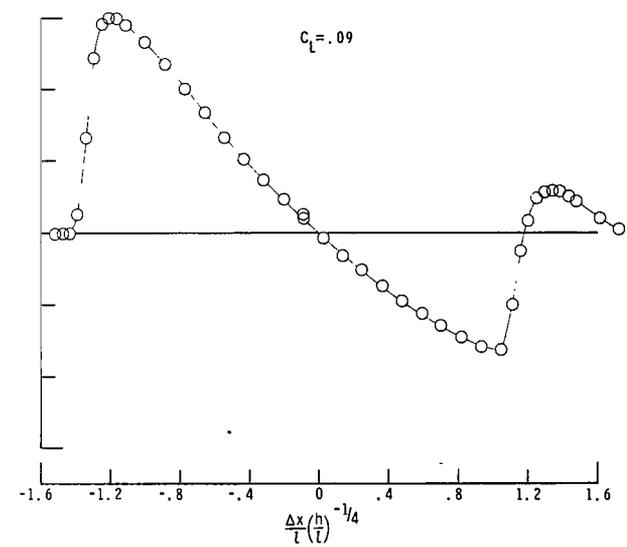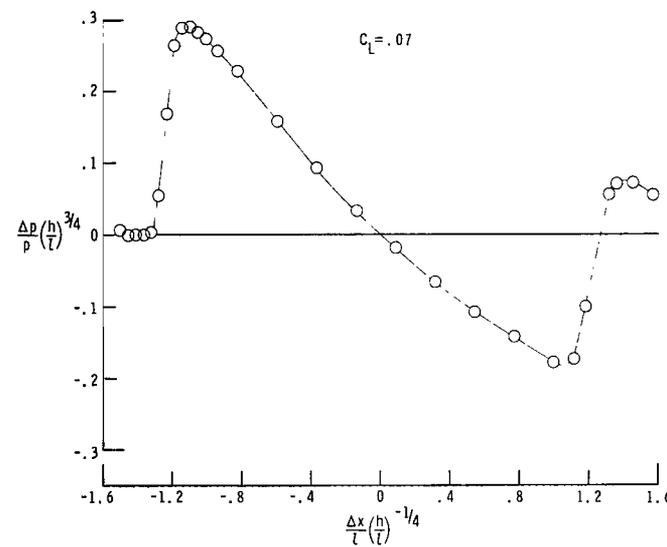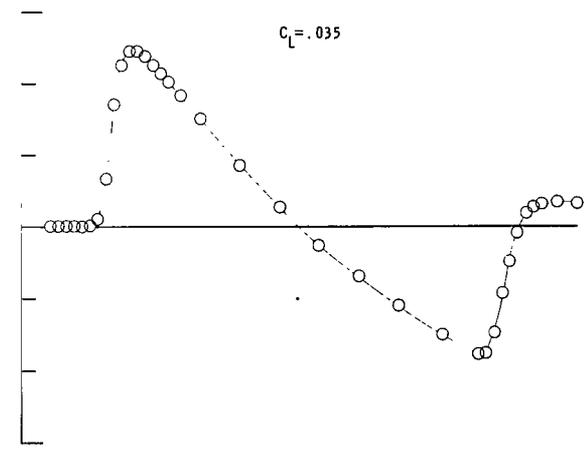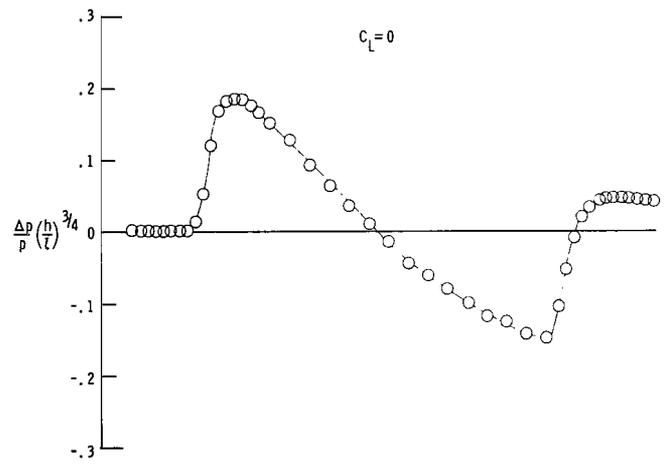
(f)   M = 4.63;   h/l = 2.

Figure 5.- Concluded.

Experiment   o

Theory   ———

M=2.3   M=2.96   M=4.63

$\frac{\Delta p}{p}\left(\frac{h}{l}\right)^{3/4}$

$C_L=0$ $C_L=0$ $C_L=0$

.2

.1

0

-.1

-.2

$\frac{\Delta p}{p}\left(\frac{h}{l}\right)^{3/4}$

$C_L=0.1$ $C_L=0.1$ $C_L=0.09$

.3

.2

.1

0

-.1

-.2

-.3

-1.2 -.8 -.4 0 .4 .8 1.2   -1.2 -.8 -.4 0 .4 .8 1.2   -2.0 -1.6 -1.2 -.8 -.4 0 .4 .8 1.2 1.6 2.0

$\frac{\Delta x}{l}\left(\frac{h}{l}\right)^{-1/4}$ $\frac{\Delta x}{l}\left(\frac{h}{l}\right)^{-1/4}$ $\frac{\Delta x}{l}\left(\frac{h}{l}\right)^{-1/4}$
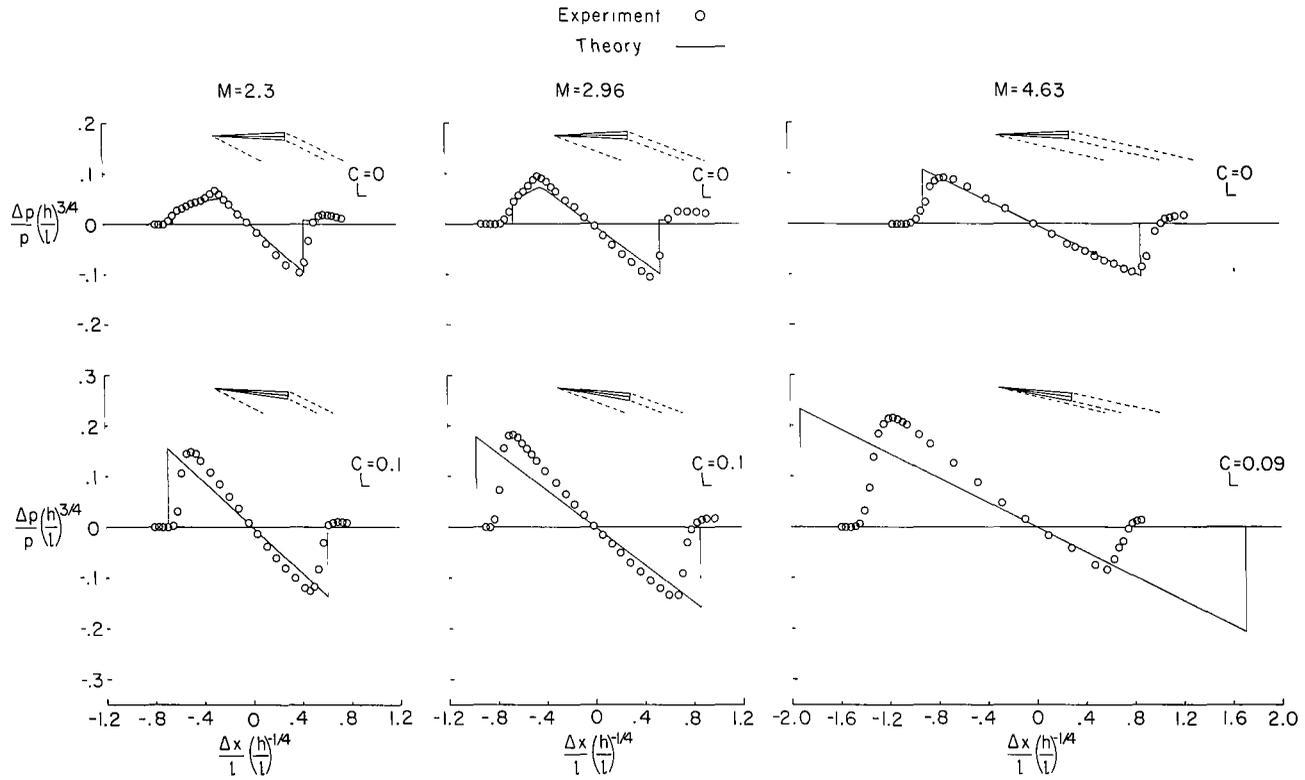
Figure 6.- Experimental and theoretical pressure signatures for model A at selected
values of M and C_L. $h/l = 4$.
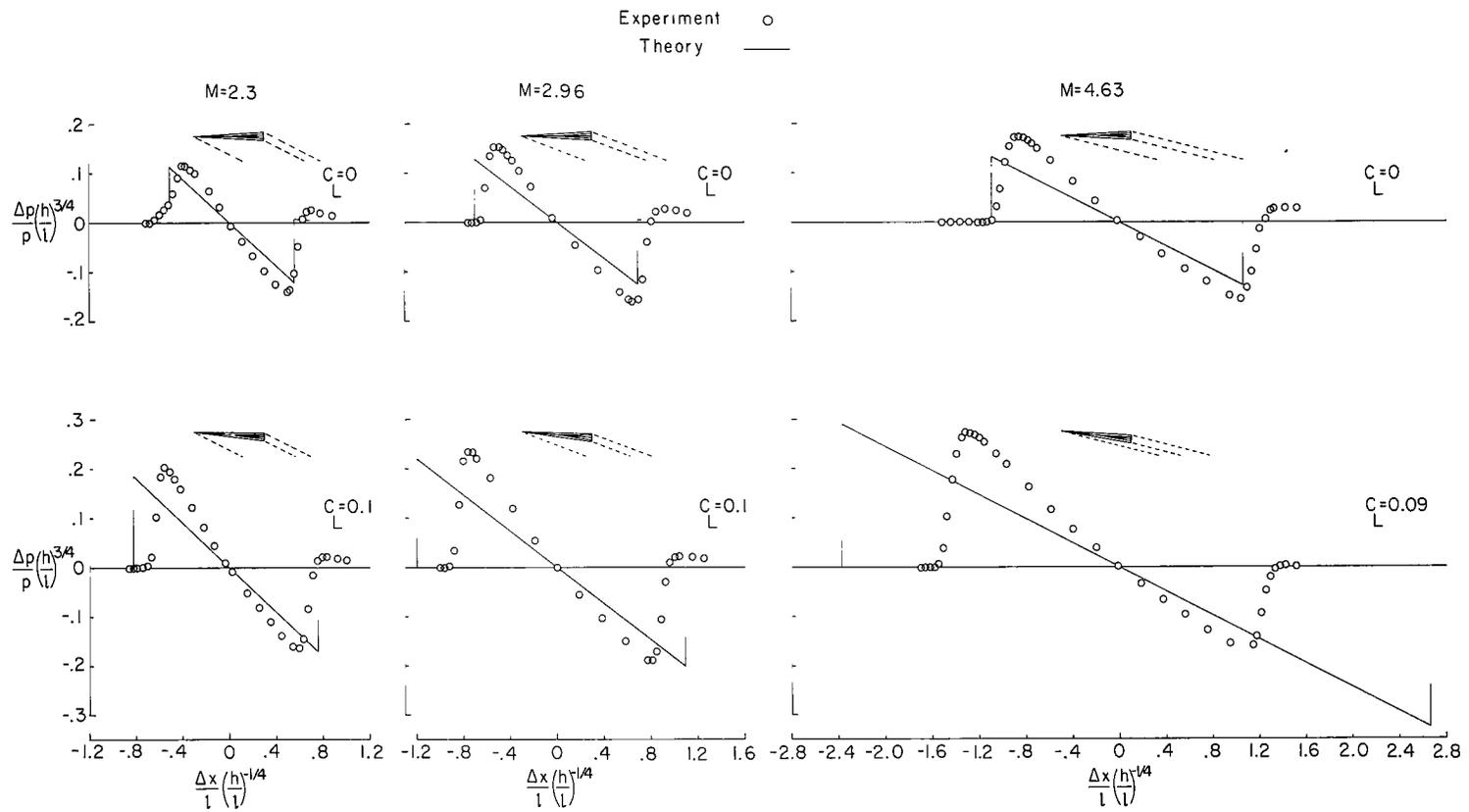
Figure 7.- Experimental and theoretical pressure signatures for model B at selected values

of M and C_L. $h/l = 4$.
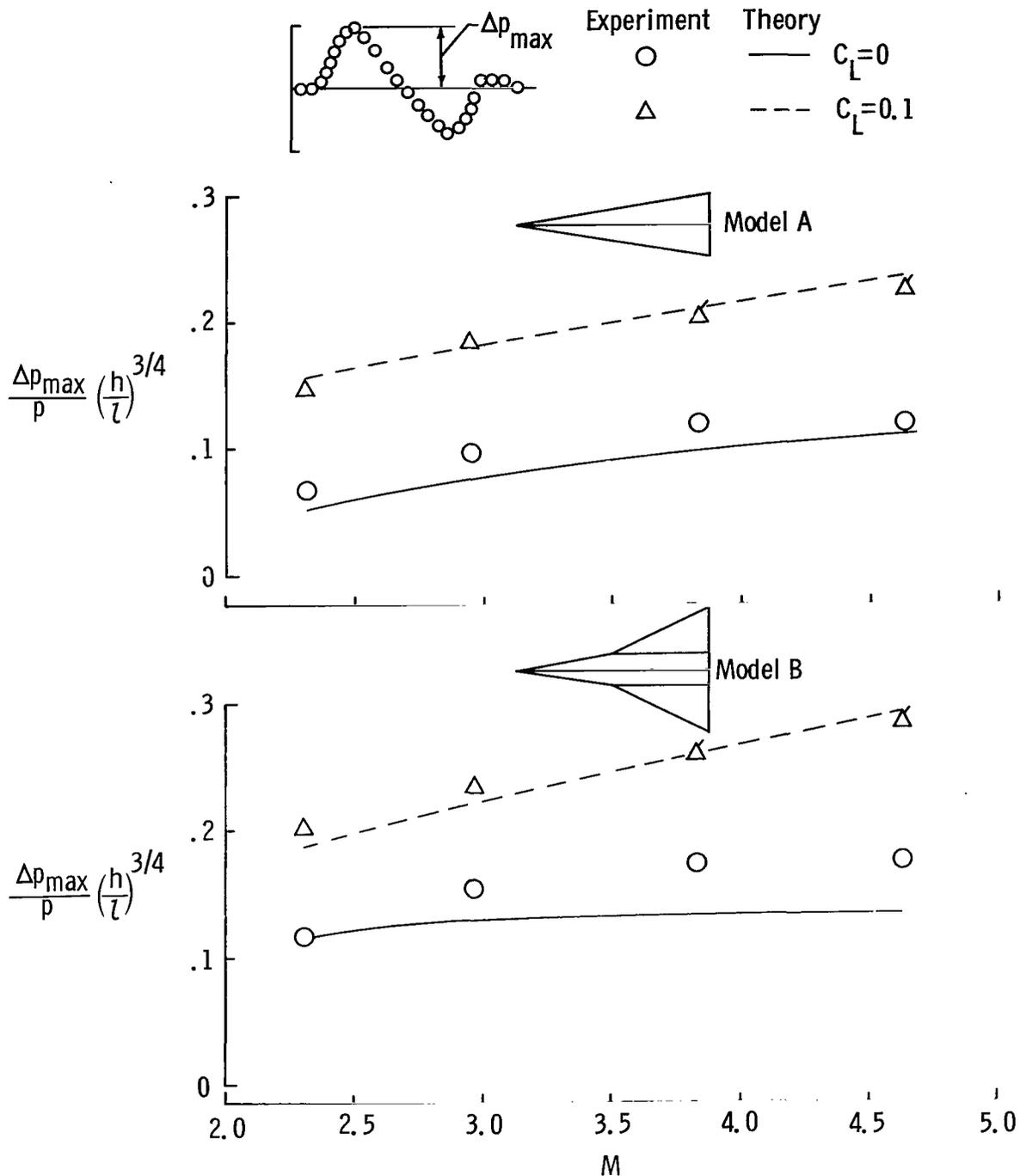
Figure 8.- Variation of maximum overpressure parameter with Mach number. $h/l = 4$. Ticked symbols denote values extrapolated from $C_L = 0.09$ to $C_L = 0.1$.
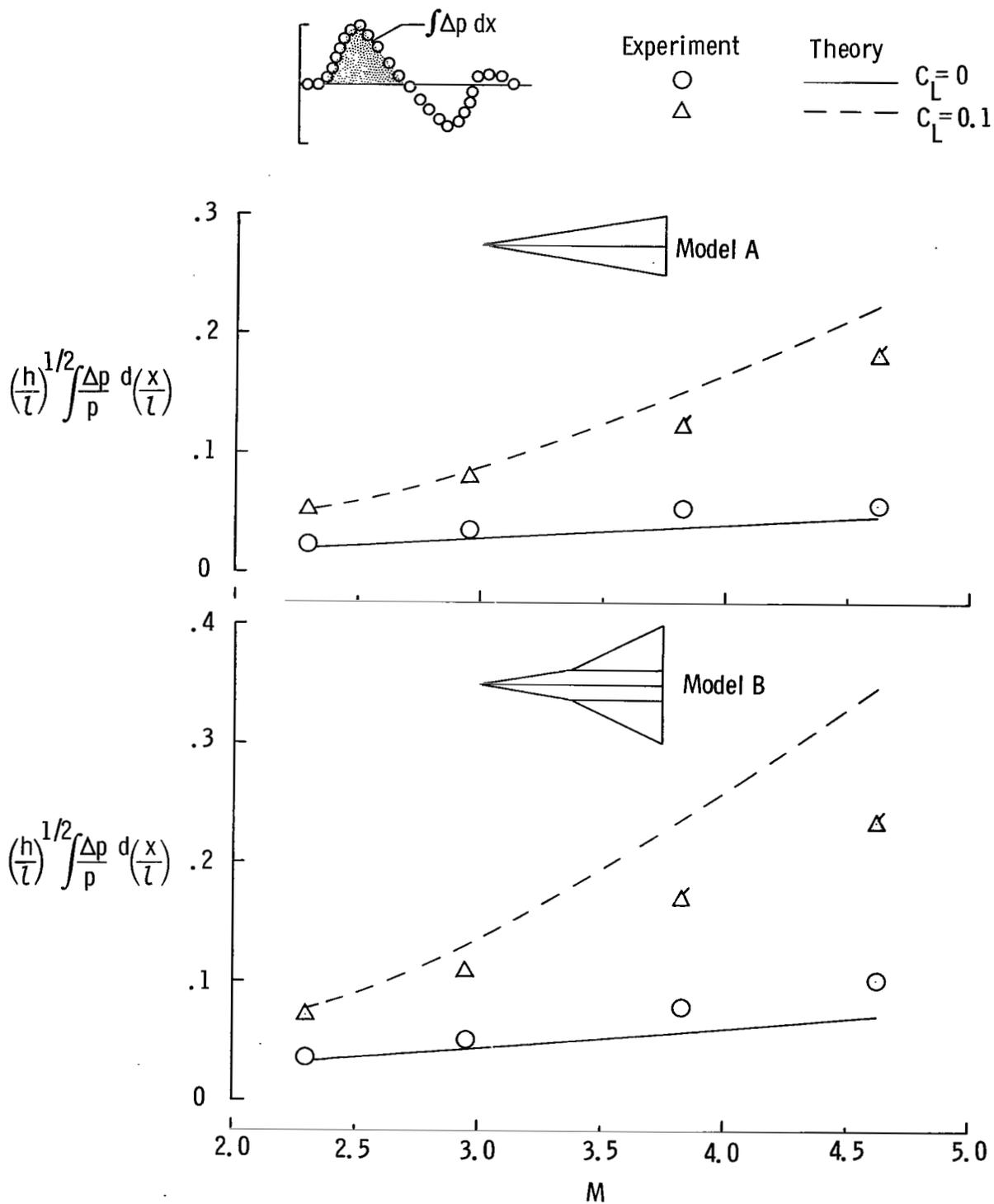
Figure 9.- Variation of signature impulse parameter with Mach number. $h/l = 4$. Ticked symbols denote values extrapolated from $C_L = 0.09$ to $C_L = 0.1$.
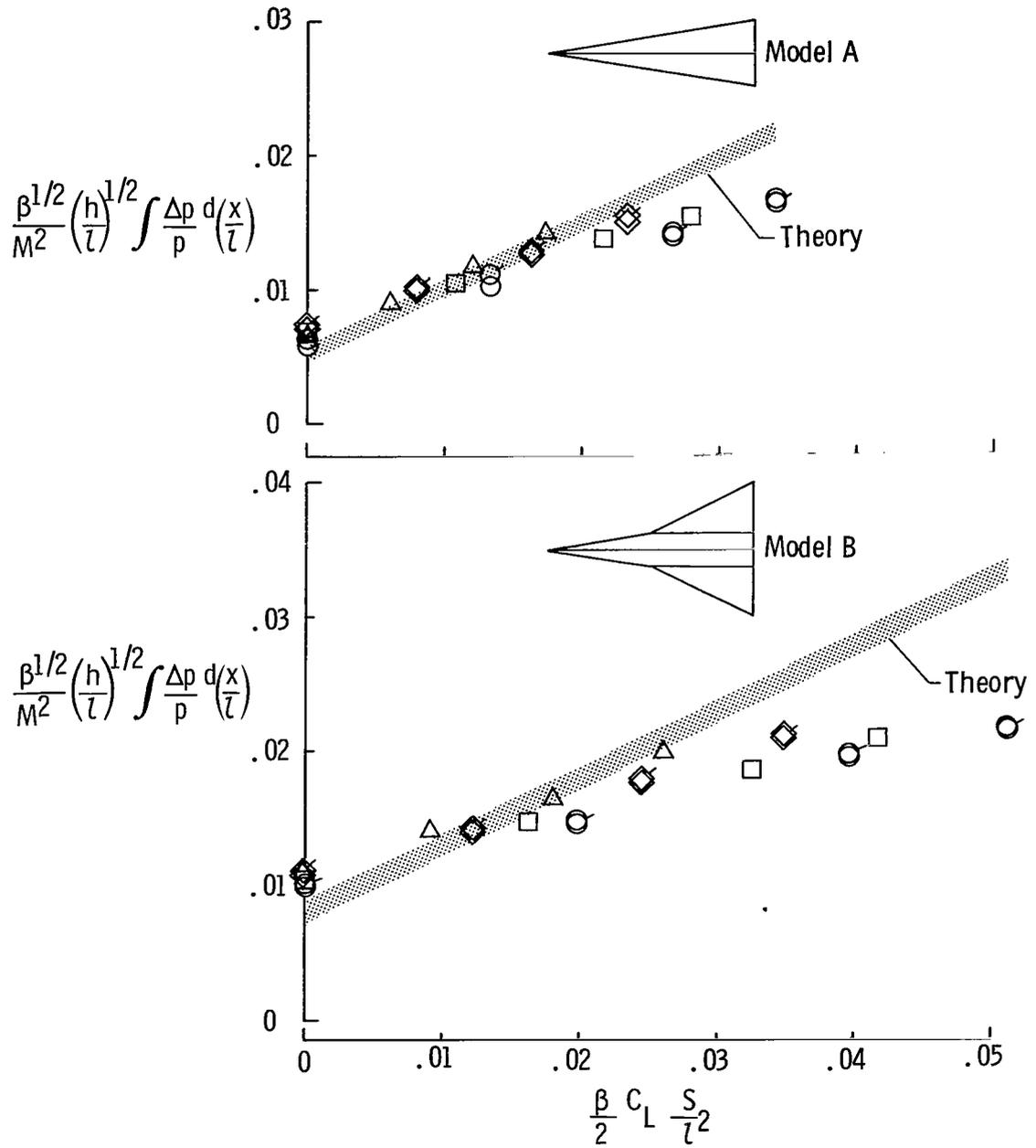
Figure 10.- Variation of signature-impulse parameter with lift parameter.

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